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by William H. Green and Joseph M. Wells

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Nondestructive Characterization of Impact Damage in Metallic/Nonmetallic Composites Using X-ray Computed Tomography Imaging

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Abstract

Characterizing internal impact damage in composites can be difficult, especially in structurally complex composites or those consisting of many materials. Many methods for the nondestructive inspection/nondestructive testing (NDI/NDT) of materials have been known and used for many years, including x-ray film, real-time and digital radiographic techniques, and ultrasonic techniques. However, these techniques are generally not capable of mapping three-dimensional (3-D) complex damage patterns, which is necessary to visualize and understand damage cracking modes. Conventional x-ray radiography suffers from the loss of 3-D information. Structural complexity and signal dispersion in materials with many interfaces significantly effect ultrasonic inspection techniques. This makes inspection scan interpretation difficult, especially in composites containing a number of different materials (i.e., polymer, ceramic, and metallic).

X-ray computed tomography (CT) is broadly applicable to any material or test object through which a beam of penetrating radiation may be passed and detected, including metals, plastics, ceramics, metallic/nonmetallic composites, and assemblies. The principal advantage of CT is that it provides densitometric (e.g., radiological density and geometry) images of thin cross sections through an object. Because of the absence of structural superposition, the images are much easier to interpret than conventional radiological images. The user can quickly learn to read CT data because images correspond more closely to the way the human mind visualizes 3-D structures than projection radiology. Any number of CT images, or slices, from scanning an object can be volumetrically reconstructed to produce a 3-D attenuation map of the object. The 3-D attenuation data can be rendered using multiplanar or 3-D solid visualization. In multiplanar visualization, four planes of view can be defined to be anywhere in an object. These visualization modes produce easily interpretable images with very good spatial resolution and excellent dimensional capability. This report discusses current applications of advanced CT imaging to characterizing impact damage in metallic/nonmetallic composites. Examples, including encapsulated ceramics in metal matrix composites, will be presented.

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1. Introduction

Characterizing internal impact damage in candidate armor materials can be difficult, especially in structurally complex materials. Many methods for the nondestructive evaluation (NDE) of materials have been known and used for many years, including x-ray film, real-time and digital radiographic techniques, and ultrasonic techniques. Conventional x-ray radiography suffers from the loss of three-dimensional (3-D) information. Structural complexity and signal dispersion in materials with many interfaces, including composite materials, can make ultrasonic inspection very difficult. X-ray computed tomography (CT) is broadly applicable to any material or test object through which a beam of penetrating radiation may be passed and detected, including metal, plastics, ceramics, metallic/nonmetallic composites, and assemblies. The principal advantage of CT is that it provides densitometric (e.g., radiological density and geometry) images of thin cross sections through an object. Because of the absence of structural superposition, the images are much easier to interpret than conventional radiological images. Any number of CT images, or slices, from scanning an object can be volumetrically reconstructed to produce a 3-D attenuation map of the object. The 3-D attenuation data can be rendered using multiplanar or 3-D solid visualization. This report discusses current applications of advanced CT imaging to characterizing impact damage in candidate armor materials, including metallic/nonmetallic composites and ceramics.

2. Principles of X-Ray CT

2.1 Technique. Figures 1a and 1b schematically show the rotate-only (RO) x-ray CT technique. The x-ray source and detector remain stationary. The object remains stationary relative to the turntable. The collimated horizontal fan beam "scans" a slice of the object as the turntable rotates 360°. The height (h) and thickness (t) of the slice is known. A set of attenuation line integrals is generated from the scan, as in equation 1,

$$\int \mu(s)\,ds = -\ln(I/I_o), \tag{1}$$

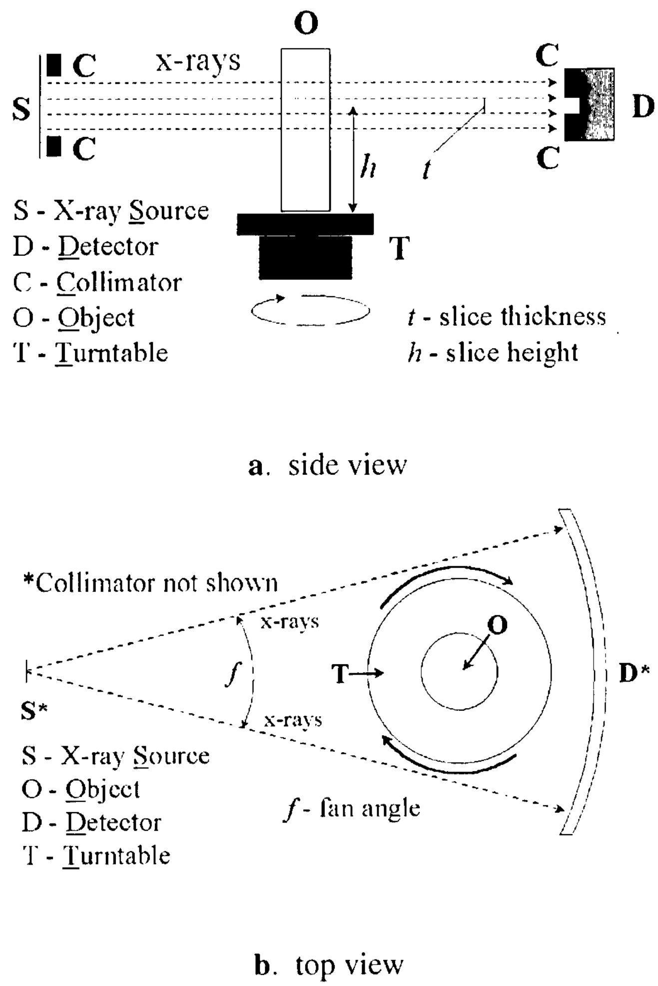


Figure 1. Schematic of the RO X-ray CT Scan Technique.

where I_0 is the intensity of the unattenuated radiation, μ is the linear attenuation coefficient, and I is the intensity of the attenuated radiation over the integrated path length (Stanley 1986). The line integrals can be conceptually grouped into subsets referred to as "views." Each view corresponds to a set of ray paths through the object from a particular direction. The views are also referred to as "projections" or "profiles," while each individual datum within a given projection is referred to as a "sample," or often just a "data point." A state-of-the-art scanner routinely collects millions of measurements per scan, each one accurately quantified and precisely referenced to a specific line of sight through the object of interest. The views from the scan are passed to the reconstruction algorithm for processing (Stanley 1986). The CT

reconstruction process yields a two-dimensional (2-D) array of numbers corresponding to the cross section of the object. The 2-D array of numbers (i.e., densitometric gray levels) is the CT image.

2.2 Volume Reconstruction. The excellent dimensional accuracy and the digital nature of CT images allow the accurate volume reconstruction of multiple adjacent slices. The slices are stacked to provide 3-D information throughout the entire object or a section of the object. The two ways of visualizing volumetric data are multiplanar reconstruction (MPR) and 3-D reconstruction. Multiplanar reconstruction displays top, front, side, and oblique slices through the object. The orientation of the top slice is parallel to the cross-sectional image plane. The front slice is orthogonal to the top slice. The side slice is orthogonal to both the top and front slices. The oblique slice can be placed on any one of the other three slices. The MPR display is similar to an engineering drawing. However, each view (i.e., top, front, side, and oblique) is a slice with finite thickness through the object, not a 2-D projection. The top, front, and side slices can be moved anywhere in the reconstructed volume. The oblique slice can be rotated through 360°.

The volumetric data is displayed as a 3-D solid object in 3-D reconstruction, and the orientation of the solid in space can be changed to facilitate different views. The solid can also be "virtually" sectioned by only displaying part of the reconstructed volume, which creates a "virtual" cutting plane on the solid that shows the x-ray density values on that plane. This plane may be orthogonal to the cross-sectional image plane. In effect, virtual sectioning shows the cutting plane as it would look if the object was actually destructively sectioned along that plane.

3. Characterization of Armor Materials

Characterizing opaque ceramic materials is required to provide both quality assurance control and damage assessment of candidate armor ceramics in either confined or applique configurations. Destructive characterization techniques are limited by the statistical sampling of selected items, which are then no longer functional for further ballistic testing or service use.

Nondestructive techniques avoid that limitation, but vary in their capability to detect and record the location, orientation, shape, and size of multiple flaw and damage types of interest in such applications, particularly where more than one type of material is involved. Using a nondestructive characterization method allows the comparison of "before" and "after" damage states in the target material.

An accurate, high-resolution, nondestructive inspection method is required to evaluate the state of damage in both "as-fabricated" and ballistically impacted candidate armor ceramic materials, including encapsulated materials. Earlier efforts utilizing ultrasonic techniques to inspect discontinuously reinforced aluminum metal-matrix-composite (MMC) materials did not indicate that ultrasonic inspection would do a suitable job. The method must be able to detect features in both an MMC encapsulating material and in the encapsulated monolithic ceramic with comparable sensitivity limits. The presence of structurally or physically different materials or their interfaces cannot interfere with detecting flaws or damage throughout the sample. Ultimately, the method should be capable of inspecting real-armor components in an encapsulated configuration. X-ray CT has these capabilities.

4. Results

4.1 Encapsulated Ceramic Silicon Carbide Plate. Encapsulating armor ceramics by cast aluminum metal-matrix-composites, Al MMCs, takes advantage of the intrinsic higher specific modulus of the MMC material and the potentially lower-cost casting fabrication method (Trevino et al. 1998). The impacted armor ceramic material must be recovered to examine the microstructural and fractographic features of the damaged material. Target systems using unconfined ceramic elements are normally incompatible with recovering the impacted ceramic fragments. Encapsulated ceramics have inherent post-impact recoverability, as long as the encapsulating material remains substantially intact. Also, the encapsulating material itself may play a significant role by preventing or minimizing bending in the ceramic rear face during ballistic impact. Reducing rear face bending of the brittle ceramic avoids high tensile bending stress, which can induce premature back surface crack initiation. Figure 2 is a schematic of

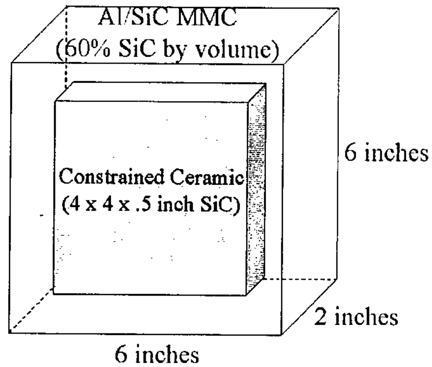


Figure 2. Schematic of SiC Plate in Encapsulating MMC Material.

sample MMC-03, in which the silicon carbide (SiC) plate is vertically and horizontally centered and closer to the front 6-in × 6-in (152.4 mm) face of the encapsulating MMC material.

The sample was scanned perpendicular to its front and back faces in translate-rotate (TR) mode from a height of 22.2 mm to a height of 122.2 mm. The cross-sectional image plane was parallel to the 2-in (50.8 mm) through thickness direction. In TR mode, the object being scanned is translated through the fan beam between finite rotations of the turntable. The source-to-object distance (SOD) in the direction of the source-to-image distance (SID) does not change. The turntable rotates after each translation is finished. The TR scan data is reorganized into a set of equivalent RO views for the reconstruction process. The SOD and SID were 662.75 mm and 930.00 mm, respectively. The slice thickness and increment were 1.00 mm, resulting in contiguous scans. Each slice was reconstructed to a 1,024 × 1,024 image matrix using 1,726 views. Scan time was about 32 min/slice, with 100 slices required to scan the 100-mm distance. The scan configuration used the 420 keV x-ray tube with the linear detector array (LDA). The tube energy was 370 keV, the current was 2.25 mA, and the focal spot was .8 mm. Figure 3 is a CT image 97.2 mm from the bottom of the sample, where the front of the sample is at the top of the image. Cracking in both the MMC material and the SiC plate is evident. The plate is not horizontally centered and is tilted in respect to the front face of the MMC material. Lastly, the plate is only about 3.5 mm to 6.0 mm away from the front face of the MMC material. The plate was displaced during the MMC casting process.

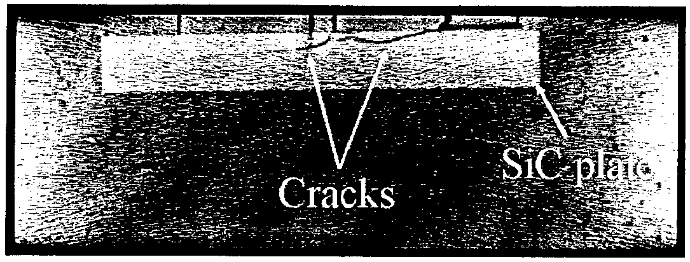


Figure 3. A CT Image at a Height of 97.2 mm in Sample MMC-03.

Figure 4 is a multiplanar visualization of the sample over the scanned 100-mm distance, with the top slice view parallel to the image plane. The top slice view is 49.5-mm high. All the views show cracks and cavities in the MMC material, including flaws directly adjacent to the SiC plate. The side slice and oblique slice views show a few faint indications of cracking in the plate. The oblique angle is 25° from the horizontal in the top slice view.

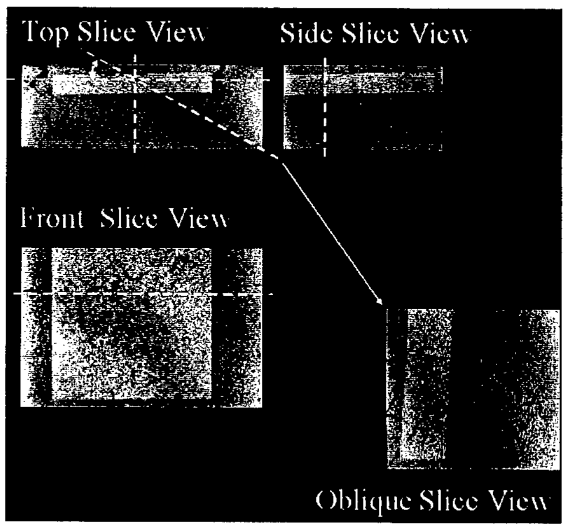


Figure 4. A Multiplanar Visualization of the Middle 100 mm of Sample MMC-03.

4.2 Impacted Ceramic Titanium Carbide Disk. An impacted titanium carbide (TiC) disk was sectioned in half. The disk was impacted by a 90% tungsten-heavy-alloy short-rod penetrator approximately at the center of one side. The thickness and diameter of the disk were approximately 25 mm and 75 mm, respectively. The entire height of one piece was scanned perpendicular to the impact face in TR mode, with the sectioned surface resting on the turntable.

The SOD and SID were 662.82 mm and 930.00 mm, respectively. The slice thickness and increment were 0.50 mm and 0.20 mm respectively, resulting in overlapping scans. Overlapping scans generally improve MPR and 3-D solid images because they result in better quality attenuation data (i.e., better photon statistics) in the overlapping regions. Each slice was reconstructed to a 1,024 × 1,024 image matrix using 1,238 views. The scan time was about 25 min/slice; 183 slices were required to scan the entire piece. The scan configuration used the 420 keV tube with the LDA. The tube energy was 350 keV, the current was 2.5 mA, and the focal spot was 0.8 mm.

Figure 5 is a CT image 18.18 mm from the sectioned surface; the impact face is at the bottom of the image. The image shows crack damage from left to right and near the back surface. Figure 6 is a multiplanar visualization of the entire piece, with the top slice view parallel to the image plane. The top slice view is 18.18 mm from the sectioned surface; all views show crack damage. The front slice and side slice views show the distribution of damage perpendicular to and in the through thickness direction, respectively, for those slices. The oblique slice view shows an area of concentrated damage in the immediate vicinity of the sectioned surface, and it shows damage shaped roughly like a ring between the top and sectioned surface of the piece. The oblique angle is 5° from the horizontal in the top slice view.

Figures 7a, 7b, and 7c are top slice and front slice views with different front slice locations. The series of top slice and front slice views shows how damage perpendicular to the through thickness direction changes with distance from the impact face. Figures 8a, 8b, and 8c are top slice views with different side slice locations. The side slice locations in the figures are 15.61 mm, 13.12 mm, and 5.64 mm to the left of the axis of the piece, respectively. The series of side views shows how damage in the thickness direction changes with distance from the line of impact. Figures 9a, 9b, and 9c are 3-D solid visualizations showing different virtual sections. Figure 9b shows the piece with approximately one-third of it virtually cut off, while in Figure 9c approximately one-half is cut off. The sectioned surfaces appear as if the piece was actually cut at those surfaces. This is an excellent way to visualize damage while viewing the entire piece.

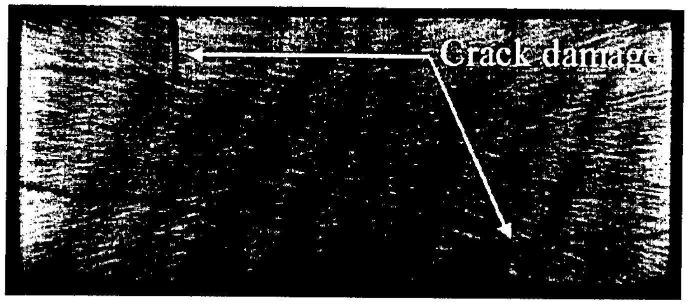


Figure 5. A CT Image 18.18 mm From the Sectioned Surface.

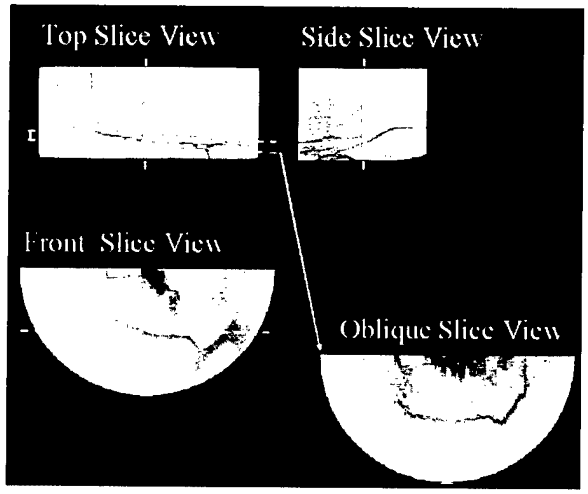
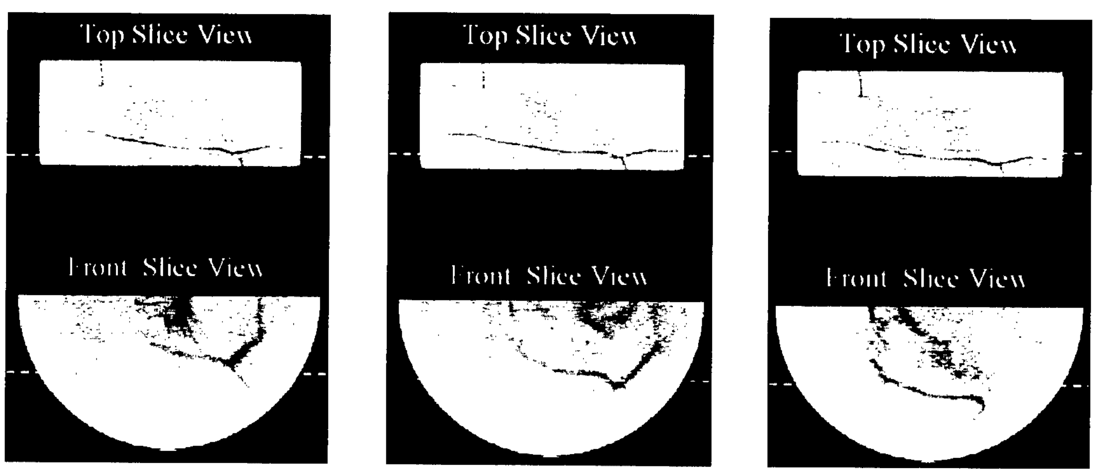
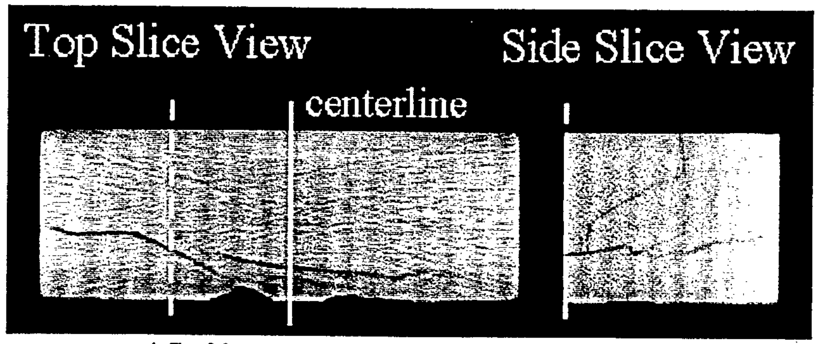


Figure 6. A Multiplanar Visualization of Impacted TiC Piece.



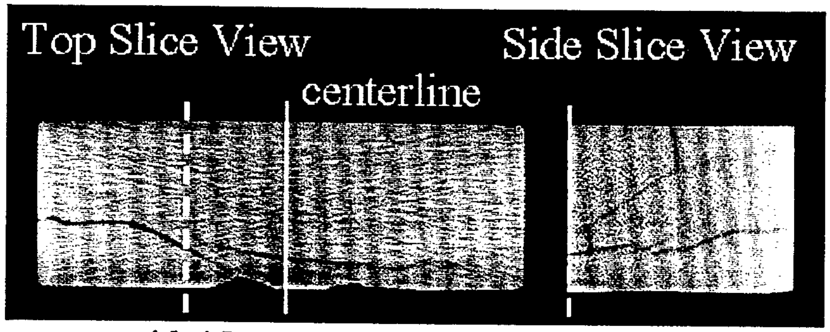
a. 2.98 mm from impact face   b. 3.98 mm from impact face   c. 5.97 mm from impact face

Figure 7. Top Slice and Front Slice Views With Different Front Slice Distances From Impact Face.



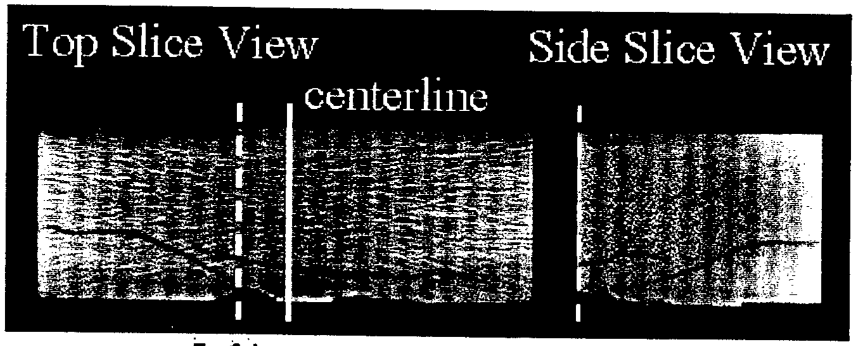
15.61 mm

a. 15.61 mm from axis



13.12 mm

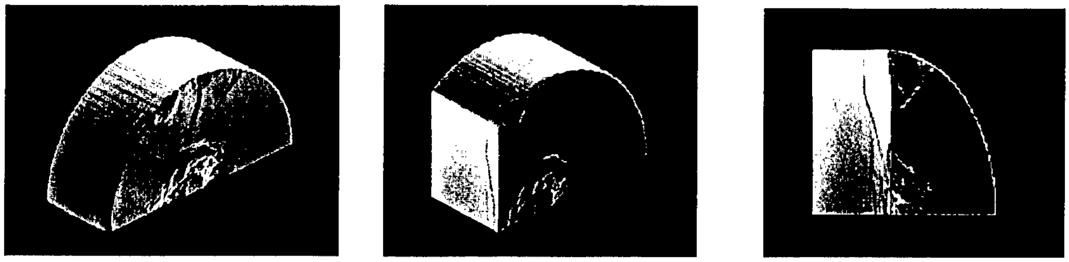
b. 13.12 mm from axis



5.64 mm

c. 5.64 mm from axis

Figure 8. Top Slice and Side Slice Views With Different Side Slice Distances From Axis (Centerline).



a. entire piece   b. two-thirds of the piece   c. one-half of the piece

Figure 9. 3-D Solid Visualizations of Impacted TiC Piece.

5. Conclusions

X-ray CT is an acceptable nondestructive technique for characterizing "as-fabricated" and ballistically impacted candidate armor materials. Pre-existing flaws, including cracking, in both the MMC encapsulating material and the monolithic ceramic SiC plate in sample MMC-03 were detected by this technique. The size, location, and orientation of the flaws were recorded to establish a "pre-impact" baseline for subsequent examination following ballistic impact. The displacement of the SiC plate was significant in both the through thickness and planar directions. Such displacement is undesirable and can be avoided in subsequent casting attempts. The displacement was adequately characterized by the nondestructive CT method, to allow for appropriate adjustments in the sample support and alignment during planned subsequent ballistic testing. The state of damage in a sample from an impacted TiC disk was characterized throughout the sample. Multiplanar and 3-D solid visualization were used to successfully characterize 3-D damage patterns.

This characterization method will be extended to other armor target configurations in the future. X-ray CT is capable of 3-D mapping complex damage patterns using multiplanar and 3-D solid visualization. The capability to characterize the pre-impact and postimpact state of damage in armor materials, combined with 3-D mapping, can be used to better understand damage cracking modes.

6. References

Stanley, J. H. "Physical and Mathematical Basis of CT Imaging." American Society for Testing and Materials (ASTM), ASTM CT Standardization Committee E7.01.07, ASTM Tutorial Section 3, Columbus, OH, 1986.

Trevino, S., G. Hauver, E. Rapacki, J. Wells, and P. Brand. "Stress Measurements in SiC Target Using Neutron Diffraction." Presented at the 21st Army Science Conference, Norfolk, VA, 15–17 June 1998.

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13. ABSTRACT *(Maximum 200 words)*
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